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# A Hands-On Approach to Statistical Mechanics Lectures: Estimation of the Boltzmann Factor Through the Viscosity Experiment of a Falling Ball

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**Abstract.** Statistical mechanics is the study of physics that relates macroscopic and microscopic parameters, often studied only with a theoretical approach, so it is relatively difficult to understand. For this reason, simple practical activities are needed to be connected with statistical mechanics, one of which is a viscosity experiment to determine the Boltzmann factor. This research was conducted to evaluate the viscosity value, coefficient of determination ($R^2$), Reynolds number, activation energy and Boltzmann factor obtained from the experiment of dropping marbles in a tube containing cooking oil at a temperature variation of 303K-333K. Viscosity is calculated based on the observed terminal velocity of the ball using Stokes' Law. The magnitude of the activation energy is analyzed using the Arrhenius equation and the probability of fluid particles flowing was calculated using the Boltzmann factor. The results showed that the viscosity of cooking oil decreased with increasing temperature, with viscosity values ranging from 44-79 cP. The Reynolds number is evaluated in the range <2300 confirming laminar flow and suitable for Stokes' law. The activation energy of viscous flow was obtained as 11.489 kJ/mol with a coefficient of determination $R^2$ = 0.87712 which indicates a strong correlation between temperature and viscosity. The estimated number of moving particles based on the Boltzmann factor is evaluated to be 1.05% - 1.58%. This research validates that the hands-on approach can explain that the increase in kinetic energy of molecules at high temperatures reduces the viscosity of the fluid, thereby increasing the probability of fluid particles flowing.

*Keywords: Boltzmann distribution, hands-on, viscosity*

## 1. Introduction

The role of statistical mechanics is very important in the field of physics, namely as a link between macro and micro analysis of properties, but it is still rarely studied from a physics education perspective [1]. Alternative approaches used by statistical mechanics instructors in universities are often limited to theoretical approaches. The characteristics of statistical mechanics are also very full of mathematical analysis and abstract and complex theories, so it is natural to find that many students experience difficulties in studying statistical mechanics [2]. One of the learning difficulties found is that students are able to understand energy density and the Boltzmann factor theoretically, but find it difficult to combine the two in problem solving [3]. In addition, it was also reported that students often have a vague understanding of concepts and difficulties in their application, so that teachers need to encourage integration between physics domains and reflect on their pedagogical approaches to build a more coherent structure of students' knowledge [4]. These students' learning difficulties will have an impact on their less than optimal understanding of statistical mechanics and can lead to a poor understanding of modern physics and quantum mechanics [5].

One of the difficulties in learning statistical mechanics is the material on the Maxwell-Boltzmann distribution function, even though the Maxwell-Boltzmann distribution is a fundamental distribution function that studies classical particles that can still be distinguished from each other. Many students are still unable to recognize situations in which the Boltzmann factor can be applied, and are unable to articulate the physical significance of the Boltzmann factor as an expression for multiplicity [6]. The Boltzmann distribution describes the state of particles with different energies at a certain temperature. Particles are assumed to not interact with each other and can occupy any energy state without restriction. The Boltzmann distribution also relates the probability density of the kinetic energy of particles of a system at thermal equilibrium. Difficulty learning the Boltzmann Factor material can impact students' weak mastery of statistical mechanics, because the Boltzmann Factor is a fundamental part [6]. In fact, statistical mechanics is a part of Advanced Physics which is very strategic in mastering science and technology related to particle distribution and energy density, which is included in Modern Physics and Quantum Physics [7]. To overcome students' learning difficulties, alternative andragogical strategies are needed that are in line with statistical mechanics learning.

As an effort to overcome learning difficulties in the Boltzmann factor material, treatment in conducting a tutorial using the guided inquiry method in deriving and applying the Boltzmann factor [6]. Although there has been an increase in students' understanding of the basics and application of the Boltzmann factor, the learning approach is still oriented towards theoretical problem solving and has not yet touched on psychomotor processes which can also actively construct knowledge in students. Furthermore, the hands-on method has been proven to be effective in improving students' conceptual understanding, when compared to traditional theoretical learning [8]. Hands-on activities help students visualize complex concepts through real-life practical activities, increase student interaction in learning and help students connect theoretical concepts with real life [9]. At the higher education level, the hands-on approach to distance learning has also been reported to show that students in hands-on classes are more committed and enthusiastic about learning, compared to traditional classes [10].

Hands-on statistical mechanics learning is still rarely studied. Even when it does exist, it's mostly conducted in the form of computer simulations. Lab View simulation is used to study probability distributions [11]. Statistical mechanics models with a thermodynamic scope are used to study heating in ideal gases [12]. Lattice modeling is used to illustrate the concepts of entropy, free energy, and thermodynamic equilibrium from a microscopic perspective [13]. While the volumetric flask with white and blue balls to demonstrate the microcanonical ensemble with small population [14]. However, the use of computer simulations also has weaknesses, namely complicated tool setup, relatively expensive, and requires special skills in its operation. This is also in line with considering the scope of the study of the Maxwell-Boltzmann distribution, which is in the form of classical particles, it should still be possible to study it with relatively simple experiments. For this reason, alternative practical activities are needed that can be carried out simply and relatively cheaply, but remain contextual and can represent the Maxwell-Boltzmann distribution.

Bachtiar et al. used a simple hands-on approach, namely the viscosity of a falling ball, to determine the Maxwell-Boltzmann distribution function [15]. In this study, the ball's falling speed at varying temperatures was measured using an Arduino Uno-based infrared sensor. Automating this time measurement can optimize the accuracy of the fall time measurement. This activity is appropriate because, from a viscosity perspective, the Maxwell-Boltzmann distribution explains that microscopically, at higher temperatures, more molecules have sufficient energy to overcome flow resistance. However, in this study, the Boltzmann distribution function is determined by using the terminal velocity of the falling ball directly, even though the fluid velocity in this method is the macroscopic velocity. Determining the Maxwell-Boltzmann distribution will be more precise if using molecular speed which is a microscopic speed. Meanwhile, the free fall method is very limited and cannot be used to obtain molecular velocity. Therefore, it would be more appropriate if the relationship between viscosity and temperature is analyzed using the Arrhenius Law, so that the activation energy is obtained, and then used to determine the Boltzmann Factor [16]. The Boltzmann Factor is the simplest representation of the Maxwell-Boltzmann distribution [6]. Therefore, to obtain a better approach, this study uses the falling ball viscosity method to estimate the Boltzmann Factor through the activation energy from the Arrhenius law.

This study aims to examine the validity of the hands-on method of falling sphere viscometry within the framework to estimate Boltzmann factor. Specifically, this research aims to: (1) Evaluate the suitability of fall ball viscometry through coefficient of determination ($R^2$) based on linear fitting from Arrhenius law; (2) Evaluate the implementation of Stokes' law in sample fluids through Reynolds number; (3) Determine the activation energy based on Arrhenius law, which relates the natural logarithm of viscosity to the inverse of temperature; (4) Determine the probability of the number of fluid particles moving, is estimated as the exponential of the activation energy and the temperature. The urgency of this research is based on the increasing attention to students' difficulties in interpreting the Boltzmann factor practically and contextually, which has a significant impact on the mastery of quantum physics and solid-state physics. However, previous research by Bahtiar still shows the scientific error of determining the magnitude of the Maxwell-Boltzmann distribution by applying terminal velocity directly, making this research important to conduct [15]. This study has several limitations. First, the research was limited to cooking oil samples, which may affect the generalizability of the findings. Second, the falling-ball viscometry measurement method used a narrow tube, which does not include wall effects in this study, which is important for viscosity interpretation. Therefore, the results should be interpreted with caution regarding wall and end effect calculations. The results of this study are expected to enable students to implement theoretical knowledge of statistical mechanics in real-world activities, particularly the Boltzmann distribution.

## 2. Methods

### 2.1. *Research Design*

This research is a laboratory experiment with a hands-on fall ball viscometry approach. The hands-on approach in this study defined as an active learning strategy, where participants directly manipulate temperature as the independent variable. The dependent variable is the travel time of the falling ball, which is correlated with fluid viscosity, to construct cognitive bridge of abstract statistical thermodynamics concepts like Boltzmann distribution. The Boltzmann factor is determined from the activation energy value obtained from the relationship between viscosity and temperature. By using viscometry hands-on experiment bridges the gap between theoretical Boltzmann factor and observable phenomena [16], fostering deeper cognitive engagement [17].

### 2.2. *Tools and Materials*

The tools used in this study were: an analytical balance, a beaker, a magnetic stirrer heater, a measuring cylinder, marbles, a stopwatch, a ruler, a piece of string, and a thermometer. The main material tested for viscosity was packaged palm cooking oil. Cooking oil, as one of the most commonly used fluids in everyday life, has viscosity characteristics that change with temperature changes. The balls used were marbles with a mass and diameter of 8,583 x $10^{-2}$ kg and 1,725 x $10^{-2}$ m respectively. The fluid is first heated using a hot plate, then poured into a measuring cylinder (Figure 1.a). Then, the marbles were dropped into the cooking oil in a measuring tube with a volume of 100 mL (Figure 1.b).


**a. Fluid Heating Mechanism** **b. Fall Ball - Measurement Tube**

**Figure 1**. Experimental Setup

### 2.3. *Instrumentation*

The ball's fall time was measured using a digital stopwatch on an Android device, and its trajectory length was measured using a ruler. The marble's mass was measured using an analytical balance. The marble's radius was measured using a micrometer screw gauge. The fall time and trajectory length were then recorded manually in Microsoft Excel. The fluid temperature was measured using a glass rod thermometer. The fluid was heated while being stirred at 200 rpm using a magnetic stirrer hot plate. All data were analyzed in Microsoft Excel, while graphing and plotting into curves were done using Origin Pro software.

### 2.4. *Procedure*

Fluid viscosity is measured using the falling ball method and analyzed using Stokes' law. The free-fall method is one of the most commonly used methods for viscosity measurement due to its simplicity and its relatively accurate results for Newtonian fluids [18]. The marbles were attached with string to facilitate retrieval after they fell to the bottom of the measuring cylinder. A 150 mL fluid was heated while stirring, and after reaching 333K, it was poured into a 100 mL measuring cylinder. The initial heating volume was higher to prevent evaporation. The balls were dropped directly onto the surface of the fluid (100 mL volume) until they reached a height of 100 mL. The ball's fall time was measured at varying temperatures from 303K to 333K. The experiment was repeated until the variation in fluid viscosity with temperature was obtained. The research procedure was carried out according to Figure 2.

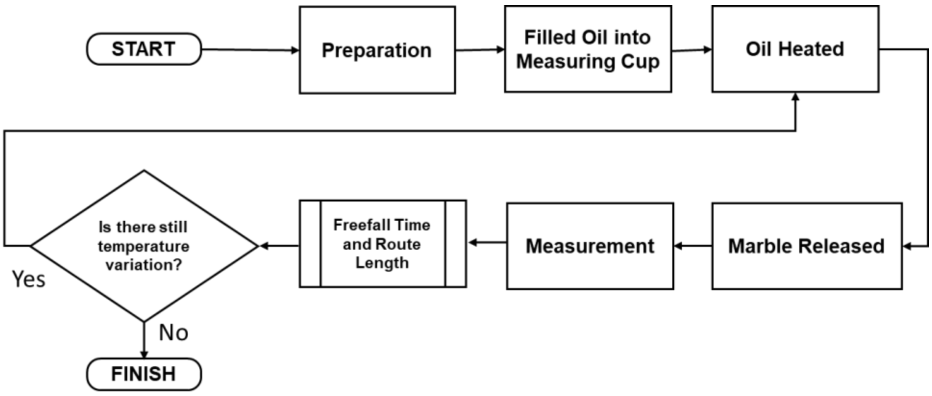


**Figure 2**. Research Procedure Flowchart

Viscosity analysis in time variation can be reviewed macroscopically with Stokes' law, while at the microscopic level through the Boltzmann Factor. The ball's falling speed data is calculated as the ratio of the path length to time. Fluid viscosity is calculated according to Stokes' equation based on the ball's falling speed. Fluid viscosity based on Stokes' law in the falling ball experiment is according to equation (1)

$$\eta = \frac{2gr^2(\rho_b - \rho_f)}{9v_t} \tag{1}$$

where $\eta$ as viscosity coefficient (Pa.s atau cP), $g$ as gravitational acceleration (m/s$^2$), $\rho_b$ as density of the ball (kg/m$^3$), $\rho_f$ as fluid density (kg/m$^3$), and $v_t$ as terminal velocity of the falling ball (m/s).

The activation energy is obtained from Arrhenius' law, using the gradient of the natural logarithm of viscosity against the inverse of temperature [19].

The magnitude of the activation energy based on Arrhenius' law is given in the Equation (2)

$$E_a = \mathrm{m} \times R \tag{2}$$

where $E_a$ as Activation Energy (Joule), m as gradient of the ln $\eta$ curve with respect to 1/T, and R as ideal gas constant.

The gradient of the Arrhenius plot was analyzed using linear fitting, the suitability of which was assessed from the coefficient of determination ($R^2$). If $R^2$ value is in the interval 0.999 - 1, then the data is in accordance with linear regression [20]. In this study, the coefficient of determination ($R^2$) was determined from the slope of the Arrhenius plot, which connects Lnη with the inverse temperature ($T^{-1}$). The agreement of experimental data with Stokes' law is evaluated using the Reynolds number. The Reynolds number is a number that determines whether a fluid flow is laminar, transitional, or turbulent [21]. If the Reynolds number is between 400 and 2000, the fluid is laminar. If the Reynolds number is between 1000 and 4000, the fluid is turbulent. If it is in between these two categories, the fluid is transitional [22]. The Reynolds number is given by Equation (3).

$$N_{Re} = \frac{D_{pipe} v_t \rho_f}{\eta} \tag{3}$$

where $N_{Re}$ as Reynolds Number, $D_{pipe}$ as Diameter of Pipe (m), $v_t$ as Final Velocity of a Ball Falling in a Fluid (m/s), $\rho_f$ as Density of fluid (kg/m3), and η as Viscosity of fluid (Pa.s or cP).

The Boltzmann factor parameter, which indicates the probability of the number of particles that can flow at a temperature variation, is obtained from the exponential of the activation energy as a function of temperature. The Boltzmann factor is calculated by the equation (4).

$$P = \exp\left(-\frac{E_a}{k_B T}\right) \tag{4}$$

where $P$ as Boltzmann's Factor, $E_a$ as Energy of Activation (Joule), $k_B$ as Boltzmann Constant, and $T$ as Absolute Temperature (Kelvin).

## 3. Results and Discussion

From this experiment, the fluid velocity, viscosity, Reynolds number, coefficient of determination, activation energy, and Boltzmann factor were obtained. Viscosity is one of the physical properties of fluids that describes the internal resistance of a substance to flow. Fluid velocity and viscosity are macro quantities, while the Boltzmann factor is a micro quantity. The Boltzmann factor indicates the possible number of particles that can move at a certain temperature. The macro and micro quantities in this study are related by the Arrhenius law.

### 3.1. *Fluid Viscosity and Velocity as Temperature Varies*

The behavior of fluid velocity and viscosity against temperature is shown in Figure 3, which shows the relationship between viscosity and fluid flow velocity against temperature. Fluid flow velocity and viscosity were obtained using Stokes' Law through the falling ball method. Both velocity and viscosity are macro quantities. In the velocity-temperature curve (purple), it can be seen that the fluid flow velocity increases with increasing temperature. The slope of the curve can indicate that changes occur slowly or that the increase in temperature does not significantly affect the ball's velocity, which can be caused by relatively small changes in viscosity or limited measurement accuracy, considering that time measurements are only through eye observation using an Android stopwatch.

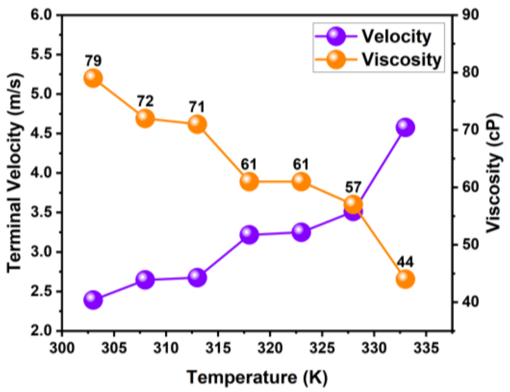


**Figure 3**. Viscosity curve and terminal velocity of a ball as a function of temperature.

The viscosity-temperature curve (orange) shows a decrease in viscosity with increasing temperature, indicating that the fluid's viscosity increases with heating. The measured viscosity ranges from 44 cP to

79 cP, at temperatures ranging from 303K to 333K, respectively. The graph also shows that the fluid's velocity increases as the fluid's viscosity decreases. Physically, this relationship indicates that the higher the fluid temperature, the easier it is for the ball to move through the fluid due to the reduced viscous frictional force.

Viscosity is a fluid property that indicates internal resistance to flow or deformation that occurs due to shear forces (Widyanto dkk., 2024). Secara mikroskopis, viskositas mencerminkan gaya kohesi antar molekul fluida dan transfer momentum antar lapisan molekul yang bergerak dengan kecepatan berbeda. The results of viscosity measurements obtained in this study are supported by measurements of the viscosity of unused cooking oil at room temperature, which is 67 cP [24]. Furthermore, the range of viscosity values for palm oil is similar, namely 20 – 45 cP at room temperature to 60°C [25]. The existence of differences indicates the need for improvements in measurement methods, especially time measurement, for example using an automatic system based on infrared sensors and Arduino [15]. Automatic time measurement will reduce errors and increase measurement accuracy.

### 3.2. *Reynolds Number*

The suitability of a fluid for evaluation using Stokes' law is evaluated according to the Reynolds number. The resulting plot of Reynolds number against temperature is given in Figure 4.

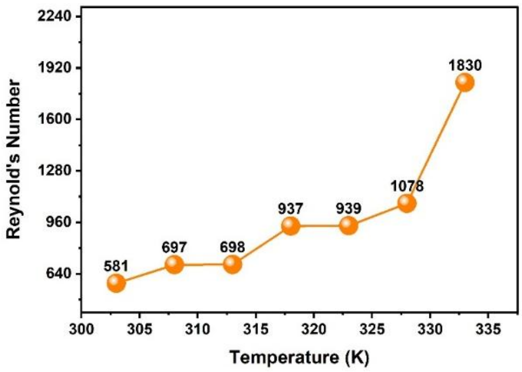


**Figure 4**. Reynolds number of palm oil in 303 – 333K.

The Reynolds number value is in the range < 2300 confirming laminar flow in the fluid, so that its viscosity can be tested using Stokes' law.

### 3.3. *Activation Energy*

The natural logarithm graph of viscosity versus the inverse of temperature shows a linear relationship with a positive upward slope. Figure 5 shows that as the ln η value increases, the 1/T value also increases, indicating a decrease in temperature. This pattern consistently indicates that the fluid experiences an increase in viscosity as the temperature decreases. The activation energy of cooking oil is 11.489 kJ/mol, which is the amount required for cooking oil particles to move.

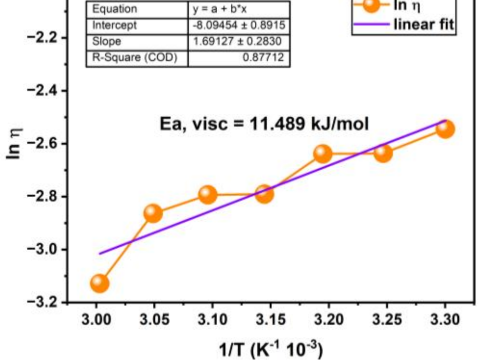


**Figure 5**. Activation Energy Value of Palm Oil Based on Arrhenius Plot Evaluation

The concept of activation energy (Ea) was first introduced by Svante Arrhenius in the context of chemical kinetics, but was later extended to explain various thermoactivation processes, including viscous flow in fluids. Activation energy is the minimum energy required for a molecule to overcome a potential energy barrier in order to move from one equilibrium position to another. In the phenomenon of viscosity, the activation energy of viscous flow (Ea,visc) describes the energy barrier that a molecule must overcome to move past its neighboring molecules[26]. Potential energy barrier caused by intermolecular cohesion. At low temperatures, only a small proportion of molecules have sufficient kinetic energy to overcome this barrier, so the fluid tends to be thicker (high viscosity). Conversely, at high temperatures, more molecules have energy above the activation energy, so flow is facilitated and viscosity decreases [27]. In accordance with the research of Fasina & Colley (2008), the viscosity of vegetable oil decreases exponentially with increasing temperature, which validates the use of the Arrhenius model in this experiment [28]. The use of the Arrhenius equation has proven to be very accurate in modeling the viscous behavior of cooking oil at varying temperatures [29].

The activation energy value for viscous flow varies depending on the type of fluid. For cooking oil, the activation energy generally ranges from 20 - 40 kJ/mol, reflecting the strength of the interactions between the triglyceride molecules that make up the oil[28]. The results of the activation energy measurements in this study were lower, namely in the range of 79 - 104 kJ/mol at a temperature of 383-413 K [30]. And also obtained the activation energy value for vegetable oil is 11.32 to 3.85 kJ $mol^{-1}$ [31].

### 3.4. *The Estimation of Boltzmann Factors Value*

The probability of fluid molecules moving according to temperature variations, the Boltzmann factor graph (relative P) against temperature shows an almost linear increasing trend. Figure 6 presents an increase in temperature with an interval of 303-333K the relative pressure value also increases from $10.453 \times 10^{-3}$ to $15.765 \times 10^{-3}$, which indicates a large probability, out of 1000 particles there are 10 particles that may be able to move at a temperature of 303K and only about 15 particles that can move at a temperature of 333K. The slope of the graph is quite constant and not too steep indicating a stable relationship between temperature and relative pressure.

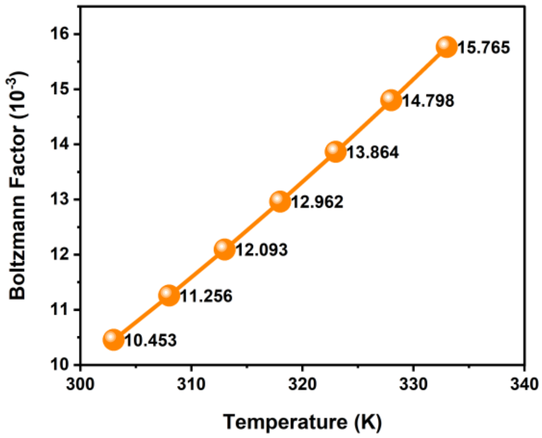


**Figure 6**. Boltzmann factor profile showing the probability of frying oil particles increasing with increasing temperature

This shows that increasing the temperature causes an increase in the kinetic energy of the particles, so that the relative pressure of the system also increases gradually and in a controlled manner. The Maxwell-Boltzmann distribution function is used for particles that are mutually distinguishable. The Maxwell-Boltzmann distribution is a statistical distribution function that describes the probability that a molecule has a certain energy at a given temperature [32]. In the context of statistical thermodynamics, the Boltzmann distribution states the number of molecules occupying a given energy level E at a temperature T. The Boltzmann factor, exp(-Ea/RT), represents the fraction of molecules that have an energy equal to or greater than the activation energy at a given temperature. In the context of viscous flow, this factor indicates the proportion of molecules that are able to overcome the energy barrier to flow.

At low temperatures, the Boltzmann factor is small, meaning only a small fraction of molecules have sufficient energy to flow, resulting in a high viscosity. Conversely, at high temperatures, more molecules have energy above the activation energy, increasing the proportion of molecules capable of flowing, and decreasing viscosity. Analysis of the proportion of molecules capable of flowing can also be related to absolute rate theory or transition state theory [33]. According to this theory, the viscous flow process can be viewed as a process in which molecules must reach a transition state with higher energy before they can move to a new position.

### 3.5. *Strengh and Limitation of This Study*

A major strength of this study is its pedagogical and practical accessibility. By utilizing the falling ball method with common cooking oil, it provides a highly reproducible, cost-effective framework to demonstrate the complex microscopic principles of the Boltzmann distribution in an undergraduate laboratory setting. This lab demonstrated a strong integration of Stokes' Law, the Boltzmann distribution, and the Arrhenius equation in explaining viscosity phenomena. The empirical data robustly aligns with the Arrhenius-type exponential decay. However, the study has certain limitations. First, the temperature range was restricted to 60°C for safety reasons, which limits the number of data points for the Arrhenius plot compared to automated rheometers. Second, the falling ball method assumes an infinite fluid medium; slight systemic errors may occur due to wall effects from the graduated cylinder.

## 4. Conclusion

Based on research that has been conducted regarding the analysis of the effect of temperature on the viscosity of cooking oil based on Stokes' Law and Boltzmann Distribution, several things can be concluded as follows: First, temperature has a significant effect on the viscosity of cooking oil, confirming that the increase in kinetic energy of molecules at high temperatures weakens the cohesion forces between molecules so that the internal resistance to flow is reduced. Second, the Stokes' Law method proved effective in measuring the viscosity of cooking oil. The Reynolds number values obtained under all experimental conditions were below 2300 ($N_{Re} < 2300$), validate the assumption of laminar flow and the validity of Stokes' Law. Third, the relationship between viscosity and temperature follows the Arrhenius equation very well, indicated by with determination coefficient $R^2 = 0,87712$. The activation energy of viscous flow obtained was 11,489 kJ/mol, within the range of literature values for vegetable oils (20 - 40 kJ/mol). This value reflects the strength of interactions between triglyceride molecules and the energy required for molecules to shift positions. The Boltzmann factor showed a significant increase with increasing temperature, indicating that the proportion of molecules possessing sufficient energy to overcome flow resistance increases exponentially with increasing temperature. The consistency between the experimental viscosity ratio and theoretical predictions validates the Boltzmann statistical approach in explaining the macroscopic properties of fluids. Overall, this research successfully answered the research problem and achieved the stated objectives of the lab. The research results have both academic value and practical implications for studying the Boltzmann distribution function with a hands-on approach.

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